Sample Entropy

Subjects: Cell & Developmental Biology

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Definition

Sample entropy, fractal dimension, Lyapunov exponent used as nonlinear measures, and assessment of the variability of the center of pressure during standing using force plate.

1. Introduction

Postural control is a term used to describe how the central nervous system regulates sensory information from other systems to produce adequate motor output to maintain a controlled upright posture. Postural control is a complicated phenomenon that combines both postural orientation and postural equilibrium. Postural orientation involves the active alignment of the trunk and head in relation to the line of gravity, the base of support, the visual surround and internal references. Sensory information from somatosensory, vestibular, and visual systems are integrated and the relative weights placed on each of these input data depend on the objectives of the motor task and the environmental context [1]. Postural equilibrium involves the coordination of movement strategies to stabilize the centre of body mass during both self-initiated and externally induced perturbations of stability. Therefore, the selected specific response strategy depends not only on the characteristics of the external postural displacement but also on the individual expectations, goals, and previous experiences.

The most common technique used to quantify postural control in upright stance is the assessment of the variability of the center of pressure (CoP). However, in recent years wearable sensors, as well as motion capture systems, are becoming increasingly common method for evaluating postural stability. The advantage of these methods is the ability to evaluate the posture stability in 3D [2][3]. However, the information obtained from these methods cannot be unequivocally interpreted from a physiological point of view. The CoP is in fact a measure of whole-body dynamics and thereby represents the sum of various neuro-musculoskeletal components acting at different joint levels. Furthermore, the CoP's time series is two dimensional. Although the two components of the signal, anterior–posterior and medial–lateral are often analyzed separately: They represent the output of a unique integrated system. As a consequence, the utility of static posturography in clinical practice is somehow limited and there is a need for reliable approaches in order to extract physiologically meaningful information from stabilograms. Therefore, the techniques of CoP signal evaluation have been recently described by using the dynamic approach. Nonlinear measures are capable of capturing the temporal component of the variation in CoP displacement with regard to how motor behavior develops over time. Therefore, these measures allow for quantifying regularity, adaptability to environment, stability [4][5], and complexity [6]. In approach reviewed in this paper, many authors assume that complexity can be defined as a compromise between order and disorder and between simplicity and complication [6]. Thus, complexity is related to the properties of stability and adaptability that characterized healthy systems and which could be lost with aging and disease. Nonlinear tools for evaluating the above-mentioned postural control properties include the largest Lyapunov exponent and Hurst exponent, recurrence quantification analysis (RQA), as well as fractal dimension and entropy families [4][7][8].

Sample entropy (SampEn) is one of the various types of entropy measures. This coefficient is used to determine the regularity of postural sway and quantifies the temporal structure of the signal by calculation the probability of that two similar sequences with the same number of data points remain similar when another data point is added [9]. In other words, SampEn (m, r, N) of a dataset of length N is the negative natural logarithm of the conditional probability of two successive counts of similar pairs (Chebyshev distance less than a tolerance size of r) of template size m and m + 1 without allowing self-matches. Chebyshev distance is also called maximum value distance and it examines the absolute magnitude of the differences between two vectors or points [10]. An advantage of SampEn is the independence of data length [11]. However, Richman and Moorman [11] advised caution when using datasets less than 200 points. The increased values of SampEn indicate larger irregularity of the CoP, which is more random and less predictable. Lower SampEn values show that the CoP signal is more regular and predictable, which is associated with less complexity of structure [12]. As complexity is crucial to the flexibility in adaptation to the surroundings, this lower complexity of physical movement translates into lower flexibility and higher rigidity of postural control [13]. Conversely, higher SampEn, which reflects increased complexity, is interpreted as improved self-organization and an effective strategy in postural control [7].

Fractal dimension (FD) is another measure that indicates the complexity of the CoP signal by describing its shape [14]. It shows the complexity and self-similarity of physiological signals. In characterizing the complexity of the CoP path, FD describes the activity of the sensorimotor system in organizing available afferents and the extent to which a person utilizes the base of support available to them [15]. In the peculiar case of the CoP trajectory, a change in FD may indicate a change in control strategies for maintaining a quiet stance. Currently, many algorithms calculate fractal dimension: Higuchi algorithm [16], Maragos and Sun algorithm [17], Katz algorithm [18], Petrosian algorithm [19], and box-counting method [20]. The most appropriate method for calculating the FD for biological signals is the Higuchi algorithm. It does not depend on the binary sequence and in many cases is less sensitive to possible noise [21].

Lyapunov exponent (LyE) is a well-defined tool to characterize the chaotic behavior of the signal. As a nonlinear parameter, this exponent measures the rate of loss of information from chaotic time series. The human dynamic stability characterized by LyE measures the resistance of the human locomotor control system to perturbations [22]. It quantifies how well an individual can keep a stable posture under perturbations in the environment. A higher LyE points to the capability of a more rapid response of balance control in different body movements [23]. In order to facilitate the reading of the general sense of low and high values of nonlinear indices in this review, Table 1 was created. Table 1 provides brief definitions of each coefficients in relation to the assessment of postural control in base on CoP time series.

Table 1. Description of nonlinear measures calculated for center of pressure (CoP) time series signal.

Nonlinear Coefficients	Low Value	High Value
Sample entropy (SampEn)—a measure of the regularity and complexity of a signal and the amount of attention devoted to the performance of a given task. Values are comprised between 0 (perfectly regular sway) and 2 (totally irregular and unpredictable sway) [9].	1. Regular CoP time series. 2. Sign of possible pathology. 3. The system may not respond flexibly to a given destabilizing stimulus. 4. Rigidity for postural control. 5. System unable to successively adapt to new changes in the environment.	1. Irregular CoP time series. 2. Sign of a healthy, alert biological system. 3. System ready for the occurrence of an "unexpected" stimulus.
Fractal dimension (FD)—provides an indication of the complexity of a signal by analyzing the entire signal and describing its shape and may be indicative of a change of the control strategies used for upright balance [24].	A signal with a fractal dimension equal to 1 would indicate a completely stationary signal over time. An impossible situation in which a person stands completely still without swaying.	Randomly generated data or data with too high a noise component, then the fractal dimension converges to 2 [25].
Lyapunov exponent (LyE)—its positive value is considered a necessary and sufficient condition for the presence of chaos in the system. LyE provides a measure of the local stability of a dynamical system [7].	Indicates the rigidity of the system and the inability to adapt to the environment [26].	Indicates the ability to react faster to destabilizing stimuli and to better control the balance [26].

Different techniques, methods, and various quantitative and qualitative variables measured have been employed in the literature to objectify postural control. Considering that the interest in the dynamic approach has been growing recently, it seems necessary to collect existing data related to the use of chaos indicators to assess postural control. Until now, not many reviews on the use of nonlinear analysis to evaluate postural stability have been found. Most of the manuscripts deal only with individual nonlinear indicators and are not reviews. The reviews which have been

found relate to general descriptions of nonlinear measures (mainly approximate and multiscale entropy) and their application or mathematical calculations. Cavanaugh, et al. [27] reviewed the theoretical foundation and limitations of the traditional postural stability model. Following cerebral concussion on athletes without postural instability showed that approximate entropy (ApEn) had detected a subtle change in postural control in the absence of postural instability. Gow, et al. [28] made the systematic review and it has revealed significant heterogeneity in the way Multiscale Entropy Analysis (MSE) is applied to CoP displacement data. Authors highlighted that significant variability in methodological approaches may impact results and their interpretations. They recommend to establish a few factors: The minimal amount of time for data collection, the physiological frequencies to evaluate, the inclusion of healthy controls, sampling rate for data acquisition, way of data filtration, and assigning appropriate values of m—the length of reconstructed vectors (i.e., length of the data segment being compared) and r—the tolerance threshold (i.e., similarity value for comparing reconstructed vectors). The purpose of Busa and van Emmerik [29] paper was to review basic elements and current developments in entropy techniques which had been used to identify how MSE can provide insights into the complication of physiological systems operating at multiple time scales that underlie the control of posture. Authors reviewed the evidence from the literature providing support for MSE as a valuable tool to evaluate the breakdown in the physiological processes that accompany changes due to aging and disease in postural control. This evidence emerged from observed lower MSE values in individuals with multiple sclerosis, idiopathic scoliosis and in older individuals with sensory impairments. At the end, Tang, Lv, Yang, and Yu [25] provided the most comprehensive literature review by examining the various complexity testing techniques for time series data and their application in fields of economics, life science, earth science, engineering, and physics. They distinguished three complexity measures groups: Fractality theory—which focuses on self-similarity and entropy—for the disorder state of a system and methods which explore data dynamics by investigating the strange attractor in phase-space. The authors have operated in a very broad and sophisticated area, showing techniques for counting and interpreting the results. Moreover, they underlined that the above-mentioned groups complexity testing techniques are closely related to or even depend on each other. One year later, van Emmerik, et al. [30] reviewed fundamental concepts of dynamic systems as variability, stability, and complexity of human movement. From this review, it was evident that these important concepts cannot be considered interchangeable and in future research should be distinguished carefully.

2. Sample Entropy

Regarding the use of sample entropy for postural stability evaluation, a total of 510 papers were found in PubMed (5 records), Science-Direct (325 records), EBSCO (176 records), and Google Scholar (4 records). In total, 33 papers were submitted for the analysis (Table 2).

Table 2. Data extracted from reviewed articles for sample entropy, where: *—significant differences.

Study and quality	Study group	Age (years)	Protocol/ Conditions	Plate and sampling rate (Hz)	m, r and fourth-order low pass Butterworth filter	Results/ Findings
Group I: Children/ Young/ Older adults						

[31] Quality: 10/11	Hypnotic susceptibility: 11 lows and 11 highs	22.9±1.8 23.2±2.4	4 trials (30s): E (easy - stable support); D (difficult - unstable support); B (basal, EC), MC (mental computation)	NI-DAG 6.9.3; 100Hz	m = 2, r = 0.2 (no data)	SampEn_ML (Highs) (B/ MC): E: 0.07±0.04/ 0.08±0.03 D: 0.10±0.02/ 0.09±0.02 SampEn_ML: D > E* Support x Task interaction: D > E* only during B. MC increased SampEn only in E*
[32] Quality: 10/11	Y: 14 OA: 11	23±2 73±6	2 trials standing (102.4s) with EO and EC	Win- Posturo; 40Hz	m = 3, r = 0.3 (no data)	Significant vision effect in: AP (EO/ EC): Y: 1.091±0.193/ 0.966±0.158* OA: 0.988±0.243/ 0.905±0.282* ML (EO/ EC): Y: 1.084±0.213/ 0.961±0.191* OA: 0.964±0.255/ 0.902±0.282*

[33] Quality: 10/11	Y right - handed: 22	24±3.2	10 trials standing (30s): 5 evenly distributed load and 5 unevenly distributed load. The specific loads held by the subjects were 1, 3, 5, 7, and 9 kg. Each trial was performed two times	AMTI AccuSway; 200Hz	m = 2, r = 0.2 (6Hz)	Significant weight × side interactions in SampEn_ML and AP: SampEn_left (loaded) limb < SampEn_right (unloaded) limb*. A Tukey post hoc: SampEn_AP was different at the 5, 7, and 9 kg loads. Only the 9 kg load was different for ML entropy. The resultant SampEn_ML tended to decrease with increasing load magnitude in the evenly and unevenly distributed load
[34] Quality: 10/11	Fallers/ Non fallers: 30/ 45	74.4±9.0	2 trials (60s) with EO and EC	AMTI BP400600-2K; 1000Hz	m = 3, r = 0.2 (1Hz)	EO/ EC: 0.52±0.35/ 0.36±0.24 EC for (Fallers/ Non fallers): 0.33±0.23/ 0.42±0.24
[35] Quality: 10/11	AA: 10 FA: 15 LA: 8 NA: 5	76.3±9.7 76.7±8.0 81.9±9.3 79.4±7.0	1 trial standing (20s) with EO	Kistler; 100Hz	(no data)	AP/ ML: AA: 0.93/ 0.73 FA: 0.79/ 0.52 LA: 0.79/ 0.68 NA: 0.78/ 0.62
[9] Quality: 10/11	Y: 21 OA: 25	22.5±2.0 69.4±3.4	Normal standing with EO and dual-task (2 discrete and 2 continuous). Each trial (60s)	AMTI ORG-6-1000; 500Hz	m = 2, r = 0.2 (no data)	SampEn_AP and ML: Y > OA

[36] Quality: 10/11	YO: 22 MO:37 OO: 31	65.4±2.3 74.6±2.7 85.4±4.4	6 limits of stability trials: 3 on firm, 3 on foam pad	Bertec 5046; 100Hz	m = 2, r = 0.2 (no data)	YO/ MO/ OO in firm plate: AP: 0.049±0.018/ 0.070±0.026/ 0.097±0.040 ML: 0.021±0.009/ 0.029±0.015/ 0.039±0.020 YO/ MO/ OO in foam plate: AP: 0.071±0.017/ 0.092±0.039/ 0.111±0.040 ML: 0.031±0.012/ 0.039±0.018/ 0.047±0.022
[37] Quality: 10/11	NP (Non-pregnant): 10 P1 (Pregnant I trimester): 10 P2: 10 P3: 10	23 (22-25) 28 (21-30) 24.5 (22.2-27) 25 (23.5-29.5)	Standing with EO (120s)	Biomec; 100Hz	m = 2, r = 0.2 (10Hz)	AP/ ML: NP: 0.09 (0.07-0.10)/ 0.14 (0.11-0.20) P1: 0.06 (0.06-0.07)/ 0.09 (0.08-0.13) P2: 0.07 (0.06-0.08)/ 0.08 (0.06-0.10) P3: 0.07 (0.05-0.07)/ 0.07 (0.05-0.07)
[38] Quality: 10/11	Y: 7	22.9±1.1	10 trials (20s): without and with the VFB (visual feedback)	AMTI AccuSway; 50Hz	m = 2, r = 0.08 and 0.05 (signal estimated to 25Hz)	SampEn_AP and ML: Y (VFB) > Y

[39]FD Quality: 10/11	Y: 16	22-25	Quiet standing on a soft support surface with EO 4 times (20s): before training, 1 min after, 30 min after, 24 hours after	Kistler 9286AA; 100Hz	m = 3, r = 0.02 (no data)	SampEn_ML > SampEn_ML_ 24h after training
[40]LyE Quality: 10/11	Y: 15 OA: 15	22.1 ±1.7 68.3 ±2.7	4 trials (90s): shoulder wide feet distance with EO and EC; narrow feet distance with EO and EC	AMTI OR6-6-1000; 1000Hz	m = 2 and 3, r = 0.1, 0.15, 0.2, 0.25, 0.3 (data download sampled from 1000Hz to 100Hz)	Y, OA: SampEn_AP: EO < EC* OA: SampEn_ML: EO < EC*
[41] Quality: 10/11	3 y.o (years old): 16 4 y.o: 18 5 y.o: 23	3 years (42.3±3.2 months) 4 years (52.4±3.8 months), 5 years (65.3±3.6 months)	4 trials standing (40s): Standing on rigid surface with EO and EC; standing on a foam surface with EO and EC. For both EO conditions, the children were watching a movie	AMTI; 100Hz	m = 3, r = 0.2 (12.5Hz)	AP in EO/ EC: 3.y.o: 0.79± 0.29/ 0.75 ±0.24 4.y.o: 0.92 ±0.25/ 0.79± 0.22 5 y.o: 0.62± 0.30/ 0.65± 0.25 ML in EO/ EC: 3.y.o: 0.82±0.38/ 0.78±0.37 4.y.o: 0.83± 0.31/ 0.93±0.34 5.y.o: 0.63±0.30/ 0.60±0.27 SampEn_AP_ML: main effect of age*, main effect of vision*, main effect of surface*
Group II: Disabilities/ Injures/ Diseases						

[42] Quality: 10/11	A: 11 CG: 13	10.3±1.2 10.1±1.3	3 tasks (20s) each with EO and EC repeated 5 times: standing; standing on foam surface; standing while performing a cognitive DT	Custom made strain gauge force plate; 200Hz	m = 3, r = 0.05 (no data)	SampEn: A < CG*. Task × Group interaction*: SampEn_foam < SampEn_other conditions Vision × Group interaction for CG*: SampEn: EC < EO
[43]FD Quality: 10/11	CWJ: 11 CG: 11	33.3±6.7 33.1±6.8	3 trials standing (45s) with: EO, EC, EO and normal speaking (DT)	AMTI OR6-5-2000; 200Hz	m = 2, r = 0.2 (10.5 Hz)	CWJ, CG: SampEn_EC_DT > SampEn_EO* SampEn_EC_DT: CG > CWJ*
[44] Quality: 10/11	EDSG: 13 CG: 20	32.4±8.4 31.4±9.6	1 trial (30s) standing with EO and EC	Kistler; 500Hz	(no data) 10Hz	SampEn: EDSG < CG* (no differences between EO and EC) AP (EDSG/ CG)*: EO: 0.05±0.10/ 0.18±0.20 EC: 0.05±0.08/ 0.24±0.27 ML (EDSG/ CG)*: EO: 0.13±0.16/ 0.29±0.21 EC: 0.13±0.19/ 0.39±0.22

						Plane and surface significantly affected SampEn. AP (EO/EC) firm surface: DS: 0.75±0.18/ 0.72±0.16 CG: 0.97±0.37/ 0.80±0.27 ML (EO/EC) firm surface: DS: 0.69±0.07/ 0.75±0.05 CG: 0.65±0.22/ 0.60±0.14 AP (EO/EC) foam surface: DS: 0.67+0.10/ 0.65±0.09 CG: 0.56+0.17/ 0.64±0.09 ML (EO/EC) foam surface: DS: 0.68±0.03/ 0.70±0.02 CG: 0.58±0.07/ 0.57±0.05
[45]FD Quality: 10/11	DS: 10 CG: 11	29.8±4.828.4±3.9	4 trials standing (20s) with: EO and EC on hard surface EO and EC on foam pad	Kistler 9286AA; 100Hz	m = 3, r = 0.02 (no data)	

[46] Quality: 10/11	ASD: 5 CG: 5	9.2±0.45 7.4±2.06	Postural stability evaluated pre- and post-intervention under 4 trials standing (20s): Flat surface with EO and EC; foam surface with EO and EC	Bertec BP505; 100Hz	(no data) 5Hz	AP: CG/ ASD pre intervention / ASD post intervention: EO: 0.13±0.04/ 0.12±0.04/ 0.08±0.03 EC: 0.10±0.03/ 0.12±0.03/ 0.10±0.03 ML: CG/ ASD pre intervention / ASD post intervention: EO: 0.14±0.04/ 0.09±0.04/ 0.09±0.04 EC: 0.13±0.04/ 0.12±0.04/ 0.12±0.03
[47] Quality: 10/11	NP: 20 CG: 20	70.8±4.1 71.4±5.1	2 trials (30s) standing with EO and EC	Kistler 9286A; 100Hz	m = 3, r = 0.3 (no data)	SampEn: NP > CG, (NP/ CG): EO: 1.72±0.1/ 1.73±0.1 EC: 1.66±0.1/ 1.73±0.1*
[48] Quality: 10/11	CP: 30 CG: 30	8.30±2.3 9.20±1.9	6 trials (20s) standing in which no supra-postural task was performed. Next, they performed a supra-postural task requiring them to balance a marble inside a tube held in the hands	AMTI AccuSway; 100Hz	m = 3, r = 0.2 (no data)	CP, CG (AP and ML): SampEn_task performance < SampEn_quiet-standing (AP and ML) SampEn_quiet-standing: CP > CG (AP and ML) SampEn_task performance: CP < CG

[49] Quality: 9/11	CP: 30 CG: 30	8.30±2.3 9.20±1.9	6 trials (20s) standing: easy and hard functional play task conditions were repeated 3 times	AMTI AccuSway; 100Hz	m = 2, r = 0.2 (no data)	SampEn_quite-standing and task performance: CP > CG* (during task performance, differences were attenuated)
[50] Quality: 10/11	CP: 8 CG: 9	11±3.3 9.4±2.0	2 trials (30s) standing with EO before and after a maximal aerobic shuttle-run test (SRT)	Bertec FP4060-08; 1000Hz	m = 3, r = 0.05 (12Hz)	SampEn_both the pre- and post-SRT tests CP < CG
[51] Quality: 9/11	FMG: 80 CG: 49	43-70 years	4 balance tasks (60s) repeated 2 times: standing with EO; DT with EO; standing with EC; standing on foam surface with EO; standing on foam surface with EC	Wii Balance Board; 40Hz	m = 4, r = 0.35 (10Hz)	SampEn_ ML (all tasks): FMG < CG*. AP (CG/ FMG): EO: 0.082±0.08)/ 0.77±0.14 EC: 0.76±0.10/ 0.67±0.14 DT: 0.78±0.09/ 0.71±0.11 FEO: 0.70±0.08/ 0.63±0.12 FEC: 0.62±0.07/ 0.54±0.11 ML (CG/ FMG): EO: 0.96±0.06/ 0.92±0.09 EC: 0.95±0.06/ 0.88± 0.11 DT: 0.93±0.07/ 0.90±0.09 FEO: 0.83±0.07/ 0.81±0.09 FEC: 0.76±0.07/ 0.71±0.11

[52] Quality: 10/11	LAS: 18 CG: 12	66±4.3 65±4.0	3 trials (20s) of a single-leg standing with EO	AMTI AccuSway Plus; 100Hz	m = 2, r = 0.2 (5Hz)	LAS/ CG: AP: 0.35±0.16/ 0.42±0.08 ML: 0.27±0.12/ 0.37±0.08
[53] Quality: 10/11	CAI: 22 LAS: 20 CG: 24	21.27±4.59 21.65±3.56 20.96±2.10	3 trials (20s) of a single-leg standing on testing leg with EC	Bertec 4060NC; 100Hz	m = 3, r = 0.3 (5Hz)	SampEn_AP and ML: no significant differences between-group. SampEn_ML: CAI > LAS, CAI > CG
[54] Quality: 9/11	CG: 50 MS low: 34 MS mod: 27 MS high: 42	64.9±4.9 54±13.2 58.2±8.3 56.7±9.7	1 trial (30s) standing with EO. In patients with MS risk of falls (low, moderate, high) was assessed using the short form of the Physiological Profile Assessment	Bertec FP4060-05-PT-1000; 1000Hz	m = 3, r = 0.2 (10Hz)	SampEn was identified as the strongest feature for classification of low-risk MS individuals from healthy CG
[55] Quality: 10/11	CAI: 19 CG: 16	22.32±3.07 22.06±3.75	1 trial (20s) standing single-leg	AMTI OR6-5/ kinematics analysis; 100Hz	m = 2, r = 0.2 (6Hz)	SampEn_AP and ML: CAI < CG
Group III: Athletes						
[56] Quality: 10/11	D: 14 CG: 16	11.5-13.3 11-13.2	Standing (20s) with EO or EC and with or without performing an attention-demanding cognitive task (DT) (word memorization)	Custom made strain gauge force plate; 100Hz	m = 3, r = 0.05 (12.5Hz)	SampEn: D > CG, EO > EC, DT > normal trial

[57] Quality: 10/11	D: 33 CG: 22	20.3±3.3 21.3±2.3	2 trials standing (20s): quite standing with EO and dual task (stroop test)	Kistler; 20Hz	m = 2, r = 0.1 (no data)	ML (Single task/ dual task): D: 0.87± 0.22/ 1.12 ±0.24 CG: 0.85± 0.20/ 1.06 ±0.25 AP (Single task/ dual task): D: 0.75 ±0.26/ 0.97± 0.38 CG: 0.87± 0.41/ 1.00± 0.31
[58] Quality: 10/11	B: 10 CG: 10	21.5±3.1 21±1.8	3 trials standing (20s) on: two legs, one leg, toe standing (35 deg PF like in high heel)	AMTI; 100Hz	m = 2, r = 0.2 (10Hz)	(B and CG): SampEn_AP: standing both feet < one-leg standing*. A contrary trend for SampEn_ML was observed.
[59] Quality: 10/11	D: 18 CG: 30	23.3±2.6 22.2±1.8	2 trials standing (30s) with EO and EC	Lafayette 16020; 100Hz	m = 2, 3, 4 r = 0.15, 0.2, 0.25 (no data)	ML (EO/ EC): ND: 0.094 ±0.030/ 0.082±0.037* D: 0.096 ±0.028/ 0.058±0.024*
[60] Quality: 10/11	G: 10 CG: 10	21.9±1.0 22.0±1.3	3 trials (30s) with EC	Dynatronic; 40Hz	m = 3, r = 0.05 (5Hz)	SampEn: G > CG*

[61] Quality: 10/11	D: 13 CG: 13	28.0±7.0 23.0±3.0	Quiet standing with EO and EC. LOS test – stand quietly during the first 10s (1st phase) next to lean as far (2nd phase) and as fast as they were able and then to maintain this position (3rd phase). Test are repeated three times and lasted 30s	AMTI Accugait; 100Hz	m = 2, r = 0.2 (7Hz)	SampEn_EO and EC_quiet standing: D > CG. LOS_AP: D > CG (1st and 3rd phase)
[62] Quality: 10/11	D: 25 CG: 25	25.6±3.8 24.7±2.6	4 condition - unipedal standing balance tests (30s): firm surface with EO and EC; foam surface with EO; and firm surface with EO immediately after performing ten 360˚ whole-body turns. (3 trials for each condition)	Kistler 9286AA; 200Hz	m = 2, r = 0.15 (7Hz)	SampEn_AP_EC: D > CG Group x condition interaction: significant for SampEn_AP. The effect of group was significant for ML and AP
The minimum value obtained in the reviewed works: 0.021±0.009 [36]				The maximum value obtained in the reviewed works: 1.73±0.1 [47].		
Study and Quality	**Study group**	**Age (years)**	**Protocol/ Conditions**	**Plate and Sampling Rate (Hz)**	**m, r and fourth-order low pass Butterworth filter**	**Results/ Findings**

Group I: Children/ Young/ Older adults						
[31] Quality: 10/11	Hypnotic susceptibility: 11 lows and 11 highs	22.9±1.8 23.2±2.4	4 trials (30s): E (easy—stable support); D (difficult—unstable support); B (basal, EC), MC (mental computation)	NI-DAG 6.9.3; 100Hz	m = 2, r = 0.2 (no data)	SampEn_ML (Highs) (B/ MC): E: 0.07±0.04/ 0.08±0.03 D: 0.10±0.02/ 0.09±0.02 SampEn_ML: D > E* Support x Task interaction: D > E* only during B. MC increased SampEn only in E*
[32] Quality: 10/11	Y: 14 OA: 11	23±2 73±6	2 trials standing (102.4s) with EO and EC	Win- Posturo; 40Hz	m = 3, r = 0.3 (no data)	Significant vision effect in: AP (EO/ EC): Y: 1.091±0.193/ 0.966±0.158* OA: 0.988±0.243/ 0.905±0.282* ML (EO/ EC): Y: 1.084±0.213/ 0.961±0.191* OA: 0.964±0.255/ 0.902±0.282*

[33] Quality: 10/11	Y right - handed: 22	24±3.2	10 trials standing (30s): 5 evenly distributed load and 5 unevenly distributed load. The specific loads held by the subjects were 1, 3, 5, 7, and 9 kg. Each trial was performed two times	AMTI AccuSway; 200Hz	m = 2, r = 0.2 (6Hz)	Significant weight × side interactions in SampEn_ML and AP: SampEn_left (loaded) limb < SampEn_right (unloaded) limb*. A Tukey post hoc: SampEn_AP was different at the 5, 7, and 9 kg loads. Only the 9 kg load was different for ML entropy. The resultant SampEn_ML tended to decrease with increasing load magnitude in the evenly and unevenly distributed load
[34] Quality: 10/11	Fallers/ Non fallers: 30/ 45	74.4±9.0	2 trials (60s) with EO and EC	AMTI BP400600-2K; 1000Hz	m = 3, r = 0.2 (1Hz)	EO/ EC: 0.52±0.35/ 0.36±0.24 EC for (Fallers/ Non fallers): 0.33±0.23/ 0.42±0.24
[35] Quality: 10/11	AA: 10 FA: 15 LA: 8 NA: 5	76.3±9.7 76.7±8.0 81.9±9.3 79.4±7.0	1 trial standing (20s) with EO	Kistler; 100Hz	(no data)	AP/ ML: AA: 0.93/ 0.73 FA: 0.79/ 0.52 LA: 0.79/ 0.68 NA: 0.78/ 0.62

[9] Quality: 10/11	Y: 21 OA: 25	22.5±2.0 69.4±3.4	Normal standing with EO and dual-task (2 discrete and 2 continuous). Each trial (60s)	AMTI ORG-6-1000; 500Hz	m = 2, r = 0.2 (no data)	SampEn_AP and ML: Y > OA
[36] Quality: 10/11	YO: 22 MO:37 OO: 31	65.4±2.3 74.6±2.7 85.4±4.4	6 limits of stability trials: 3 on firm, 3 on foam pad	Bertec 5046; 100Hz	m = 2, r = 0.2 (no data)	YO/ MO/ OO in firm plate: AP: 0.049±0.018/ 0.070±0.026/ 0.097±0.040 ML: 0.021±0.009/ 0.029±0.015/ 0.039±0.020 YO/ MO/ OO in foam plate: AP: 0.071±0.017/ 0.092±0.039/ 0.111±0.040 ML: 0.031±0.012/ 0.039±0.018/ 0.047±0.022
[37] Quality: 10/11	NP (Non-pregnant): 10 P1 (Pregnant I trimester): 10 P2: 10 P3: 10	23 (22-25) 28 (21-30) 24.5 (22.2-27) 25 (23.5-29.5)	Standing with EO (120s)	Biomec; 100Hz	m = 2, r = 0.2 (10Hz)	AP/ ML: NP: 0.09 (0.07-0.10)/ 0.14 (0.11-0.20) P1: 0.06 (0.06-0.07)/ 0.09 (0.08-0.13) P2: 0.07 (0.06-0.08)/ 0.08 (0.06-0.10) P3: 0.07 (0.05-0.07)/ 0.07 (0.05-0.07)

[38] Quality: 10/11	Y: 7	22.9±1.1	10 trials (20s): without and with the VFB (visual feedback)	AMTI AccuSway; 50Hz	m = 2, r = 0.08 and 0.05 (signal estimated to 25Hz)	SampEn_AP and ML: Y (VFB) > Y
[39]FD Quality: 10/11	Y: 16	22-25	Quiet standing on a soft support surface with EO 4 times (20s): before training, 1 min after, 30 min after, 24 hours after	Kistler 9286AA; 100Hz	m = 3, r = 0.02 (no data)	SampEn_ML > SampEn_ML_ 24h after training
[40]LyE Quality: 10/11	Y: 15 OA: 15	22.1 ±1.7 68.3 ±2.7	4 trials (90s): shoulder wide feet distance with EO and EC; narrow feet distance with EO and EC	AMTI OR6-6-1000; 1000Hz	m = 2 and 3, r = 0.1, 0.15, 0.2, 0.25, 0.3 (data download sampled from 1000Hz to 100Hz)	Y, OA: SampEn_AP: EO < EC* OA: SampEn_ML: EO < EC*

						AP in EO/ EC: 3.y.o: 0.79± 0.29/ 0.75 ±0.24 4.y.o: 0.92 ±0.25/ 0.79± 0.22 5 y.o: 0.62± 0.30/ 0.65± 0.25 ML in EO/ EC: 3.y.o: 0.82±0.38/ 0.78±0.37 4.y.o: 0.83± 0.31/ 0.93±0.34 5.y.o: 0.63±0.30/ 0.60±0.27 SampEn_AP_ML: main effect of age*, main effect of vision*, main effect of surface*
[41] Quality: 10/11	3 y.o (years old): 16 4 y.o: 18 5 y.o: 23	3 years (42.3±3.2 months) 4 years (52.4±3.8 months), 5 years (65.3±3.6 months)	4 trials standing (40s): Standing on rigid surface with EO and EC; standing on a foam surface with EO and EC. For both EO conditions, the children were watching a movie	AMTI; 100Hz	m = 3, r = 0.2 (12.5Hz)	
Group II: Disabilities/Injures/Diseases						
[42] Quality: 10/11	A: 11 CG: 13	10.3±1.2 10.1±1.3	3 tasks (20s) each with EO and EC repeated 5 times: standing; standing on foam surface; standing while performing a cognitive DT	Custom made strain gauge force plate; 200Hz	m = 3, r = 0.05 (no data)	SampEn: A < CG*. Task × Group interaction*: SampEn_foam < SampEn_other conditions Vision × Group interaction for CG*: SampEn: EC < EO

[43]FD Quality: 10/11	CWJ: 11 CG: 11	33.3±6.7 33.1±6.8	3 trials standing (45s) with: EO, EC, EO, and normal speaking (DT)	AMTI OR6-5-2000; 200Hz	m = 2, r = 0.2 (10.5 Hz)	CWJ, CG: SampEn_EC_DT > SampEn_EO* SampEn_EC_DT: CG > CWJ*
[44] Quality: 10/11	EDSG: 13 CG: 20	32.4±8.4 31.4±9.6	1 trial (30s) standing with EO and EC	Kistler; 500Hz	(no data) 10Hz	SampEn: EDSG < CG* (no differences between EO and EC) AP (EDSG/ CG)*: EO: 0.05±0.10/ 0.18±0.20 EC: 0.05±0.08/ 0.24±0.27 ML (EDSG/ CG)*: EO: 0.13±0.16/ 0.29±0.21 EC: 0.13±0.19/ 0.39±0.22

						Plane and surface significantly affected SampEn. AP (EO/EC) firm surface: DS: 0.75±0.18/ 0.72±0.16 CG: 0.97±0.37/ 0.80±0.27
[45]FD Quality: 10/11	DS: 10 CG: 11	29.8±4.828.4±3.9	4 trials standing (20s) with: EO and EC on hard surface EO and EC on foam pad	Kistler 9286AA; 100Hz	m = 3, r = 0.02 (no data)	ML (EO/EC) firm surface: DS: 0.69±0.07/ 0.75±0.05 CG: 0.65±0.22/ 0.60±0.14 AP (EO/EC) foam surface: DS: 0.67+0.10/ 0.65±0.09 CG: 0.56+0.17/ 0.64±0.09 ML (EO/EC) foam surface: DS: 0.68±0.03/ 0.70±0.02 CG: 0.58±0.07/ 0.57±0.05

[46] Quality: 10/11	ASD: 5 CG: 5	9.2±0.45 7.4±2.06	Postural stability evaluated pre- and post-intervention under 4 trials standing (20s): Flat surface with EO and EC; foam surface with EO and EC	Bertec BP505; 100Hz	(no data) 5Hz	AP: CG/ ASD pre intervention / ASD post intervention: EO: 0.13±0.04/ 0.12±0.04/ 0.08±0.03 EC: 0.10±0.03/ 0.12±0.03/ 0.10±0.03 ML: CG/ ASD pre intervention / ASD post intervention: EO: 0.14±0.04/ 0.09±0.04/ 0.09±0.04 EC: 0.13±0.04/ 0.12±0.04/ 0.12±0.03
[47] Quality: 10/11	NP: 20 CG: 20	70.8±4.1 71.4±5.1	2 trials (30s) standing with EO and EC	Kistler 9286A; 100Hz	m = 3, r = 0.3 (no data)	SampEn: NP > CG, (NP/ CG): EO: 1.72±0.1/ 1.73±0.1 EC: 1.66±0.1/ 1.73±0.1*
[48] Quality: 10/11	CP: 30 CG: 30	8.30±2.3 9.20±1.9	6 trials (20s) standing in which no supra-postural task was performed. Next, they performed a supra-postural task requiring them to balance a marble inside a tube held in the hands	AMTI AccuSway; 100Hz	m = 3, r = 0.2 (no data)	CP, CG (AP and ML): SampEn_task performance < SampEn_quiet-standing (AP and ML) SampEn_quiet-standing: CP > CG (AP and ML) SampEn_task performance: CP < CG

[49] Quality: 9/11	CP: 30 CG: 30	8.30±2.3 9.20±1.9	6 trials (20s) standing: easy and hard functional play task conditions were repeated 3 times	AMTI AccuSway; 100Hz	m = 2, r = 0.2 (no data)	SampEn_quite-standing and task performance: CP > CG* (during task performance, differences were attenuated)
[50] Quality: 10/11	CP: 8 CG: 9	11±3.3 9.4±2.0	2 trials (30s) standing with EO before and after a maximal aerobic shuttle-run test (SRT)	Bertec FP4060-08; 1000Hz	m = 3, r = 0.05 (12Hz)	SampEn_both the pre- and post-SRT tests CP < CG

						SampEn_ ML (all tasks): FMG < CG*. AP (CG/ FMG): EO: 0.082±0.08)/ 0.77±0.14 EC: 0.76±0.10/ 0.67±0.14 DT: 0.78±0.09/ 0.71±0.11 FEO: 0.70±0.08/ 0.63±0.12 FEC: 0.62±0.07/ 0.54±0.11 ML (CG/ FMG): EO: 0.96±0.06/ 0.92±0.09 EC: 0.95±0.06/ 0.88± 0.11 DT: 0.93±0.07/ 0.90±0.09 FEO: 0.83±0.07/ 0.81±0.09 FEC: 0.76±0.07/ 0.71±0.11
[51] Quality: 9/11	FMG: 80 CG: 49	43-70 years	4 balance tasks (60s) repeated 2 times: standing with EO; DT with EO; standing with EC; standing on foam surface with EO; standing on foam surface with EC	Wii Balance Board; 40Hz	m = 4, r = 0.35 (10Hz)	
[52] Quality: 10/11	LAS: 18 CG: 12	66±4.3 65±4.0	3 trials (20s) of a single-leg standing with EO	AMTI AccuSway Plus; 100Hz	m = 2, r = 0.2 (5Hz)	LAS/ CG: AP: 0.35±0.16/ 0.42±0.08 ML: 0.27±0.12/ 0.37±0.08

[53] Quality: 10/11	CAI: 22 LAS: 20 CG: 24	21.27±4.59 21.65±3.56 20.96±2.10	3 trials (20s) of a single-leg standing on testing leg with EC	Bertec 4060NC; 100Hz	m = 3, r = 0.3 (5Hz)	SampEn_AP and ML: no significant differences between-group. SampEn_ML: CAI > LAS, CAI > CG
[54] Quality: 9/11	CG: 50 MS low: 34 MS mod: 27 MS high: 42	64.9±4.9 54±13.2 58.2±8.3 56.7±9.7	1 trial (30s) standing with EO. In patients with MS risk of falls (low, moderate, high) was assessed using the short form of the Physiological Profile Assessment	Bertec FP4060-05-PT-1000; 1000Hz	m = 3, r = 0.2 (10Hz)	SampEn was identified as the strongest feature for classification of low-risk MS individuals from healthy CG
[55] Quality: 10/11	CAI: 19 CG: 16	22.32±3.07 22.06±3.75	1 trial (20s) standing single-leg	AMTI OR6-5/ kinematics analysis; 100Hz	m = 2, r = 0.2 (6Hz)	SampEn_AP and ML: CAI < CG
Group III: Athletes						
[56] Quality: 10/11	D: 14 CG: 16	11.5-13.3 11-13.2	Standing (20s) with EO or EC and with or without performing an attention-demanding cognitive task (DT) (word memorization)	Custom made strain gauge force plate; 100Hz	m = 3, r = 0.05 (12.5Hz)	SampEn: D > CG, EO > EC, DT > normal trial

[57] Quality: 10/11	D: 33 CG: 22	20.3±3.3 21.3±2.3	2 trials standing (20s): quite standing with EO and dual task (stroop test)	Kistler; 20Hz	m = 2, r = 0.1 (no data)	ML (Single task/ dual task): D: 0.87± 0.22/ 1.12 ±0.24 CG: 0.85± 0.20/ 1.06 ±0.25 AP (Single task/ dual task): D: 0.75 ±0.26/ 0.97± 0.38 CG: 0.87± 0.41/ 1.00± 0.31
[58] Quality: 10/11	B: 10 CG: 10	21.5±3.1 21±1.8	3 trials standing (20s) on: two legs, one leg, toe standing (35 deg PF like in high heel)	AMTI; 100Hz	m = 2, r = 0.2 (10Hz)	(B and CG): SampEn_AP: standing both feet < one-leg standing*. A contrary trend for SampEn_ML was observed.
[59] Quality: 10/11	D: 18 CG: 30	23.3±2.6 22.2±1.8	2 trials standing (30s) with EO and EC	Lafayette 16020; 100Hz	m = 2, 3, 4 r = 0.15, 0.2, 0.25 (no data)	ML (EO/ EC): ND: 0.094 ±0.030/ 0.082±0.037* D: 0.096 ±0.028/ 0.058±0.024*
[60] Quality: 10/11	G: 10 CG: 10	21.9±1.0 22.0±1.3	3 trials (30s) with EC	Dynatronic; 40Hz	m = 3, r = 0.05 (5Hz)	SampEn: G > CG*

[61] Quality: 10/11	D: 13 CG: 13	28.0±7.0 23.0±3.0	Quiet standing with EO and EC. LOS test—stand quietly during the first 10s (1st phase) next to lean as far (2nd phase) and as fast as they were able and then to maintain this position (3rd phase). Test are repeated three times and lasted 30s	AMTI Accugait; 100Hz	m = 2, r = 0.2 (7Hz)	SampEn_EO and EC_quiet standing: D > CG. LOS_AP: D > CG (1st and 3rd phase)
[62] Quality: 10/11	D: 25 CG: 25	25.6±3.8 24.7±2.6	4 condition - unipedal standing balance tests (30s): firm surface with EO and EC; foam surface with EO; and firm surface with EO immediately after performing ten 360˚ whole-body turns. (3 trials for each condition)	Kistler 9286AA; 200Hz	m = 2, r = 0.15 (7Hz)	SampEn_AP_EC: D > CG Group x condition interaction: significant for SampEn_AP. The effect of group was significant for ML and AP
The minimum value obtained in the reviewed works: 0.021±0.009 [36]				The maximum value obtained in the reviewed works: 1.73±0.1 [47].		

Abbreviations: AP—anterior–posterior, ML—medial–lateral direction, EO—eyes open, EC—eyes closed, DT—dual task, Y—young, OA—older adults, AA—always active, FA—formerly active, LA—lately active, NA—never active, YO—Young-Old, MO—Middle-Old, OO—Old-Old, ASD—autism spectrum disorders, CAI—chronic ankle instability, MS—multiple sclerosis, LAS—lateral ankle sprain, CP—cerebral palsy, NP—neck pain, A—anxious children, EDSG—Ehlers–Danlos syndrome, FMG—fibromyalgia group, DS—Down syndrome, CG—control group, D—dancers, B—ballet group, G—expert gymnasts, CWJ—chronic whiplash injury, FD—study in Table 3, LyE—study in Table 4.

The assessment of postural stability using SampEn in groups of older adults, young people and children was included in 12 papers. Fourteen articles analyzed people with dysfunctions, neurological diseases, and musculoskeletal disorders. Athletes were studied only in 7 papers. Only in 3 papers [39][43][45] the results were analyzed using fractal dimension in addition to sample entropy. In one paper [40] analysis based on sample entropy was supplemented by LyE (Figure 1). All the papers were highly rated (10/11 points). The score was affected by a negative answer to question 8 (Have all important adverse events that may be a consequence of the intervention been reported?) in all of the cases and resulted in losing one point. Only three articles [49][51][54] were rated lower (9/11 points). In this case, a negative answer to question 10 (Have actual probability values been reported (e.g., 0.035 rather than < 0.05) for the main outcomes except where the probability value is less than 0.001?) had an impact.

The youngest study group was children aged 3 years (42.3±3.2 months) [41], whereas the oldest group was consisted of adults aged 85.4 ± 4.4 years [36]. Quiet standing trials with eyes open and closed were dominant in all three groups. The duration of each trial ranged from 20 to 120 seconds for the groups of older adults and young people, from 20 to 60 seconds in the second group (Disabilities/Injures/Diseases), and 20–30 seconds in the group of athletes. The CoP sampling rate was in the range of 20Hz to 1000Hz, but the most commonly used was 100Hz. Analyzing the method of SampEn calculation, most of the works did not explain on what basis and how the values of m and r were selected. In 11 papers, default values of m and r parameters (m = 2, r = 0.2) were used [63]. In 13 papers it was not stated whether the SampEn was calculated for the raw or filtered signal.

In the groups of older adults and young children, SampEn was lower for older adults compared to young people [9][32]. In the group Disabilities/Injures/Diseases, the entropy analysis showed lower values in people with injuries, dysfunctions or diseases than those in the group of healthy people. In the group of athletes, the postural sway of dancers/gymnasts was characterized by more irregular CoP sway (as exemplified by higher sample entropy) than in non-dancers. In all of the groups, the absence of vision led to a decrease in SampEn as compared to when the eyes were open. The values of entropy in the analyzed papers are in the range: 0.021 ± 0.009 [36] - 1.73 ± 0.1 [47].

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Keywords

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